Presentation

THERMAL PROTECTION SYSTEM OF THE HUYGENS PROBE DURING TITAN ENTRY: FLIGHT PREPARATION AND LESSONS LEARNED

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ABSTRACT

The entry of the HUYGENS probe in the atmosphere of TITAN on January 14th 2005 was undoubtedly a crucial phase for the success of the mission. The thermal shield completely fulfilled its role to maintain the aerodynamic shape and to protect the probe from excessive heating during its atmospheric entry.
After a short recall of the TPS architecture, the paper will focus on the work performed in 2004 within the framework of the final preparation of the mission.

Following the heat flux reassessment leading to a significant increase compared to what was considered during the development phase, it was necessary to review accordingly the performance of the Thermal Protection System (TPS) accounting for different topics:

- Eventual influence of the UV heating induced by the radiation of the flow
- Ablative behavior of the material
- Thermal modeling and thermal insulation performance and checking of the limitation of structure temperatures to allowable values.

This paper gathers a summary of tests and analysis results obtained during this last phase of mission preparation. This work was conducted by EADS-ST, with the support of ESA and NASA ARC for characterization and cross checking material modeling. It was finally drawn the conclusion that the TPS could fulfill its mission with a sufficient margin.
Finally, the main lessons learned are presented as a conclusion of this whole activity.

1. GENERALITIES ABOUT HUYGENS TPS

1.1 CASSINI - HUYGENS mission

The Cassini-Huygens spacecraft was launched on October 15th 1997. After a 7 years interplanetary journey, it has been inserted into orbit around Saturn on July 1st 2004. The Huygens probe was separated from Cassini on December 25th 2004, and finally entered the atmosphere of Titan on January 14th 2005.

1.2 Industrial organization (HUYGENS TPS)

ALCATEL SPACE was the prime contractor of the ESA program HUYGENS.
EADS SPACE Transportation was responsible for entry and descent system analyses, as well as for design, justification and manufacturing of the thermal protections of two subsystems: the Back -Cover and the Frontshield. This is summarized on Fig. 1 below.

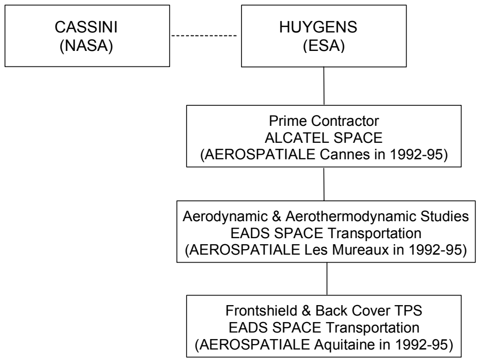

Fig. 1 : Industrial Organization (TPS only)

1.3 TPS Architecture

The frontshield was made of a sandwich structure (aluminium honeycomb + CFRP skins) and of two ablative thermal protection materials developed and produced by EADS-ST:

- AQ60/I on the front face is a felt made of short fibers reinforced with phenolic resin. AQ60/I tiles are bonded on the structure and jointed by a silicone glue.
- PROSIAL on the rear face (moderate heat flux level) is a silicone elastomere with excellent thermal properties. It includes silica hollow spheres to decrease its density and is implemented using a spraying process

The back cover was made of an aluminum shell covered with PROSIAL.

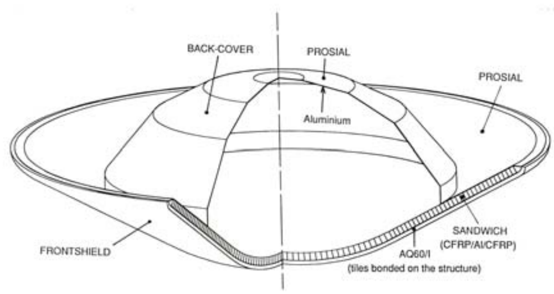

Fig. 2 : TPS architecture

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1.4 Entry conditions: (atmosphere, heat flux, shear stress, pressure)

The main constituent of TITAN atmosphere is nitrogen (N_2). Two other constituents are identified: argon (Ar) and methane (CH_4).
During entry, the methane dissociates in the shock layer, leading to the formation of CN. This molecule generates a high radiation in the narrow UV band. Though the convective heat flux is not very sensitive to atmosphere composition, the radiative heat flux can on the contrary reach very high values, especially for trajectories with highest FPA (Flight path angle).

Table 1 below summarizes the main characteristics of the probe, TPS, and environment during entry.

Table 1 - Main characteristics of HUYGENS TPS

HUYGENS Mission	Entry on Titan (Saturn's moon) after a 7 years travel with CASSINI	
Entry characteristics (development phase values)	duration	300 sec.
	max. heat flux (front face)	1400 kW/m^2 (20 sec.)
	max. heat flux (rear face)	30 to 120 kW/m²
	max. shear stress	135 Pa (area close to edge of decelerator)
	max. pressure	0.1 atm. (stagn. point)
	worst atmosphere	77% N_2, 20% Ar, 3% CH_4
Frontshield	T.P. material	AQ60/I
	Density	d = 0.28
	Thickness	17.4 to 18.2 mm
	T.P. mass	39 kg (including glue & joints)
	Structure	CFRP honeycomb
	Structure mass	32 kg
	total mass	76 kg (including 5kg PROSIAL on back face)
Rear part and back-cover	T.P. material	PROSIAL
	Density	d = 0.54 to 0.60
	Thickness	0.3 to 3.1 mm
	T.P. mass	5.2 kg
	Structure	stiffened aluminium (0.8 mm)
	total mass	17 kg
Whole Entry Module	Total height	0.97 m
	Max. diameter	2.70 m
	Total mass of the vehicle	320 kg (actual mass)

2. MISSION PREPARATION PHASE

In order to prepare the Huygens entry, the final definition of mission parameters was carried out in 2004. The performance of the thermal shield was one among all the parameters considered at system level and it was thus necessary to reassess the thermal response of the TPS. These last analyses must obviously take into account some updated information that was not yet available during the development phase ten years before. More particularly, two points were considered:

- A possible transparency of the AQ60 material in the UV wavelengths
- Updated heat fluxes, with expected values significantly higher than during the development phase.

An overview of this work is presented in the following sections, including recent results completing the previous ones already reported in [1].

3. AQ60 POSSIBLE TRANSPARENCY

3.1 Overview of the problem

As mentioned previously, due to the atmosphere composition, the entry velocity, and the shape of the probe, the heat shield undergoes both convective and radiative heat fluxes. More precisely, the radiative emission of the shock layer occurs in the narrow UV band. In the framework of studies about aerocapture mission at Titan [2,3], NASA experts identified possible uncertainties on performance of lightweight materials. Indeed, a general trend was suggested from Laser tests performed in the 80’s on several dozens of TP materials. The shorter the wavelength was, the larger became the absorption length. There is no available test result in UV wavelength for lightweight materials. The potential for in-depth absorption could thus be of concern for AQ60, since it could lead to char spallation that would significantly reduce its efficiency and lead to eventual additional heating of the underlying substructure. In order to evaluate the performance of candidate Titan TP materials exposed to UV radiation, NASA has decided to develop a specific facility based on a high-power Mercury-Xenon lamp that has a strong emission in the UV range.

3.2 Action plan

Based on above mentioned information, this topic was analyzed during the Delta-FAR (Flight acceptance review) held at the beginning of 2004. It was decided to initiate several actions in order to evaluate the influence of this phenomenon on the performance of the Huygens Frontshield.

- Status on representativeness of development phase tests wrt radiative emission in UV band

- Status on representativeness of IRS test wrt radiative emission of the flow in UV wavelength
- Low intensity radiation exposure tests at ESTEC
- High intensity radiation exposure tests at NASA

The corresponding results are presented hereafter.

3.3 Representativeness of development phase tests

Two families can be identified among the tests of the development phase: radiative and plasma tests.

The radiative tests (BATTELLE, ECT, and EQT) [1] were performed with an Infrared radiant source. No information about UV radiation can therefore be deduced from these tests.

The SIMOUN plasma tests were carried out in a pure N_2 tangential flow. There was therefore no radiation effect during these tests.

On the other hand, most of the IRS tests were performed in an atmosphere composed of N_2, Ar and CH_4. In addition, it must be highlighted that the introduction of methane was very spectacular, inducing a high brightness of the flow [4]. Thus only IRS tests can be relevant with regard to UV radiation.

3.4 Representativeness of IRS tests

During the development phase, this problem of UV radiation had not been considered, and only the total heat flux had been measured for this test campaign.

However, a synthetic analysis can be established, relying on experimental works conducted by IRS after the end of the Huygens development [4,5,6]. Indeed, an extensive characterization of Nitrogen/Methane plasma flows was undertaken from 1992 to 1998.

A specific radiometer was developed and used to measure the radiation emitted by the flow [4]. In addition, a set of emission spectroscopy measurements was done for various combinations of N_2/CH_4 mixtures [5]. This evidenced that some radiative heat flux occurred during these experiments, and that some emission could be observed around 380 nm, which corresponds to CN violet. A direct quantitative interpretation of these tests is not easy, because these are mainly local measurements in reduced solid angles. An estimation of the integrated value is provided in [6]: the radiative heat flux is 377 kW/m², which represents ≈20% of the corresponding total heat flux equal to 1800 kW/m².

Even though some uncertainty must obviously be associated to this result, it shows that the radiative component of the flux can be considered as significant for the tests that were performed in 1992.

However, no evident influence on material behavior was identified. This point was thus a first positive trend, even though the worst expected value of the radiative heat flux could be much higher than the experienced one of 377 kW/m².

3.5 Low intensity radiation exposure tests at ESTEC

As recommended by the board of the Delta-FAR, elementary characterization tests on AQ60 were performed by ESTEC in March and April 2004 [7].

AQ60 samples of 40 x 40 mm x 1 to 5 mm thick (Fig. 3) were illuminated by a spectral Xenon lamp radiating at a wavelength of 377 nm, and the intensity of the light transmitted through the samples was recorded. The transmission was then calculated by comparison with transmission obtained with calibrated neutral density filters.

Fig. 3 : AQ60 samples

The test device (Fig. 4) is operated at room temperature.

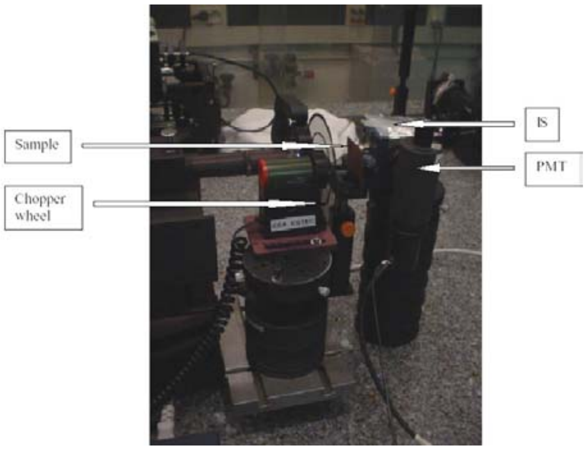

Fig. 4 : Picture of test device

(IS = Integrating Sphere; PMT=Photomultiplier)

Tests were carried out on 10 samples provided by EADS-ST. 8 of these samples were made of virgin material without coating, with different thickness between 2 and 5 mm (two 1 mm thick samples were machined by ESTEC from already tested specimen in order to complete a first set of results). The 2 other samples were made of char material issued from tested samples remaining from the 1993 ECT tests.

The results presented in the table 2 show a very low transmission in the UV through AQ60. This transmission is even lower for the pyrolysed samples.

Table 2: samples thickness and transmission calculated from the measured signal

Sample	Thickness (mm)	Transmission
V1(bis)	1.00	1.79E-04
V7(bis)	1.10	1.35E-04
V2	2.12	7.77E-06
V3	3.10	1.20E-06
V4	3.10	1.27E-06
V5	4.08	1.82E-07
V6	4.10	1.57E-07
V8	5.05	5.20E-08
P1	4.06	8.00E-09
P2	4.08	6.00E-09

(V= virgin material. P= pyrolysed material).

These very positive results constituted the first step of the demonstration that the transparency of AQ60 in UV could be considered as a negligible phenomenon for the Huygens mission.

3.6 High intensity radiation exposure tests at NASA

The completion of previous results by tests at high temperature was considered very relevant. At the Huygens Delta Flight Acceptance Review (FAR) held in Cannes in February 2004, NASA offered to test AQ60 samples for the Huygens project in a test campaign prepared at NASA Ames for analyzing the performance of lightweight TP materials when exposed to high intensity UV radiation (cf. §3.1). ESA accepted the offer and under Huygens contract with Alcatel as prime contractor, EADS-ST supplied 8 AQ60 samples (75 x 75 x 20 mm) for these tests. These samples included a central plug insert (diameter 30mm) in which several thermocouples could be installed by NASA.

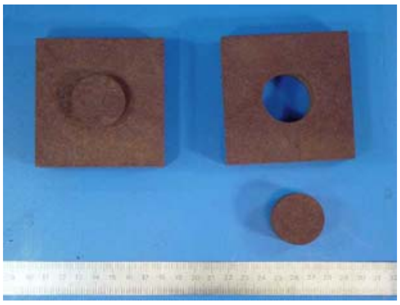

Fig. 5 : AQ60 samples for UV tests at NASA

Several tests were performed at two heat flux levels: 500 and 1500 kW/m², generated by a high-power Mercury-Xenon lamp. Reference [8] gives a complete description of this test campaign with the following positive conclusion: Tests of instrumented samples of AQ60 with UV radiation at heat fluxes representative of best estimates of the radiative heating expected during Huygens probe entry into the Titan atmosphere demonstrated that the material absorbs this radiation at the surface and is not semi-transparent at these wavelengths.

3.7 Conclusion

All the available experimental results proved that there was no transparency of AQ60 in the UV: This topic was therefore no longer of concern for the entry of Huygens at Titan.

4. INFLUENCE OF HEAT FLUX UPDATE ON TPS

Since the end of development phase, several elements contributed to update the mission and refine the entry corridor:

- Communications between orbiter and probe
- Selection of a new atmosphere model (Yelle) associated to the Strobel Gravity Wave model

The associated aerothermal environment was hence rather different from the one used during C/D phase.
The corresponding reassessment work performed in 2003 by the industrial team has been reviewed in the frame of the Delta-FAR in February 2004. In the course of this review, different heating levels have been observed between various contributions, namely EADS-ST, ESTEC-MPA and NASA ARC. Following one recommendation of the review board, it was thus created an Aeroheating Convergence Working Group (ACWG) with the objective to understand the disparities, to reconcile the various aerothermal inputs and consolidate a single aerothermal environment.

A first step of this activity was completed during the first half of 2004[9]. As many discrepancies were still observed, this work continued up to the last days before the final decision. The evolutions finally considered for TPS evaluations are shown on Fig. 6.

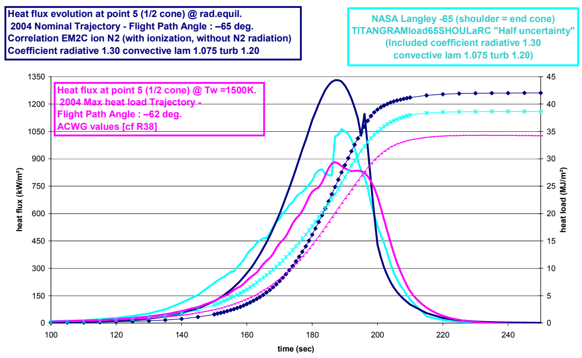

Fig. 6 : Final evaluations of heat flux (nov-2004)

As this heat flux reassessment exhibited a significant increase compared to what was considered during the development phase, it was necessary to review accordingly the performance of the TPS accounting for different topics:

- Thermal modeling and thermal insulation performance and checking of the limitation of structure temperatures to allowable values.
- Ablative behavior of the material

These topics are reported in [10] and summarized in the following sections.

5. REVIEW OF THERMAL QUALIFICATION TESTS of HUYGENS TPS

5.1 General logic of the tests

Before being used for HUYGENS, the two TP materials had been developed for a quite different application. During the development phase, from 1992 to 1995, it was thus necessary to update and complete their characterizations, particularly for AQ60.

The following objectives were reached successfully during the study, in order to demonstrate the satisfactory behavior of AQ60 in conditions representative of the HUYGENS entry:

- validation of the choice of this material
- update of the material data set thanks to thermal and thermomechanical characterization tests
- qualification of the tile arrangement (joints, steps, possible defects, micrometeoroid impact)
- thermomechanical qualification of the whole heatshield

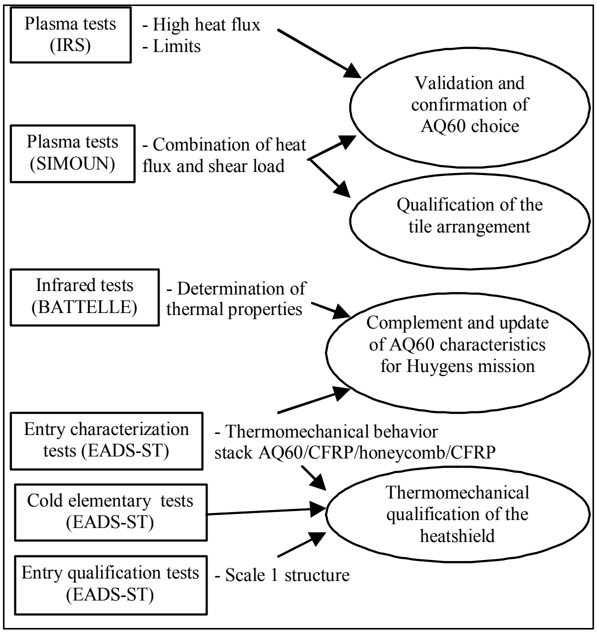

Fig. 7 : General logic of the tests

The most specific physical aspects to consider were the following:

- high heat fluxes in a non oxidizing atmosphere as representative as possible of the Titan's one (gas mixture N_2, Ar, CH_4, or pure N_2)
- combination of high heat flux and aerodynamic shear
- thermomechanical effects

Fig. 7 summarizes the main outcomes of these tests that are presented more in detail in [1].

5.2 Validation of thermal model

One essential output of the above mentioned characterization tests was the consolidation of the thermal model, which was validated thanks to the restitution of temperature measured during these different tests. Fig. 8 and Fig. 9 illustrate a good consistency of computed and measured temperatures.

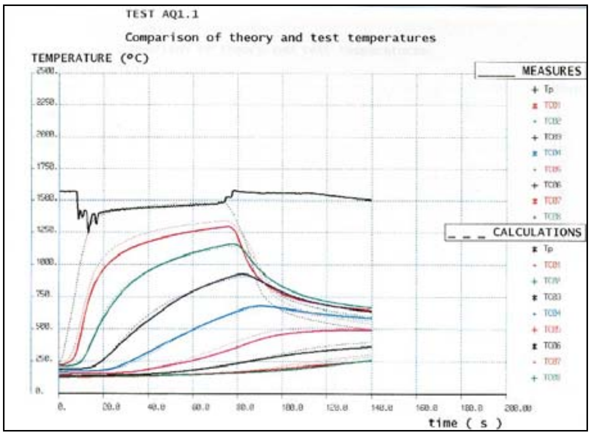

Fig. 8 : Restitution of measured temperatures during Infrared tests at Battelle Institute

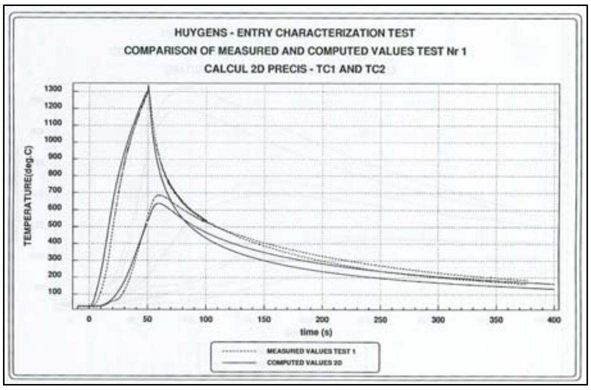

Fig. 9 : Restitution of measured temperatures during Entry Characterization Test (ECT)

However, it must be recognized that these tests only covered a limited domain of heat flux, mainly with radiative heating because there had not been any satisfactory measurement (i.e. with several in-depth thermocouples) during plasma tests performed in the framework of the development phase. Hence, the internal heat transfer was correct but a complete validation of the model was missing with an arc jet

test at the maximum level of heat flux combined with aerodynamic shearing.
This had been accepted at the end of development phase especially since such a test was not achievable at that time. However, the increase of heat flux observed in 2004 contributed to raise again this question, as it is illustrated on Fig. 10.

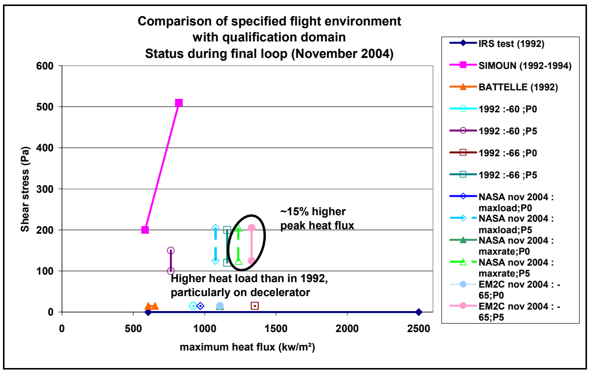

Fig. 10 : Qualification domain

Considering the good consistency of the results obtained during the development phase, it was finally stated that the available results were sufficient to authorize the mission.
A complementary arc jet test was performed at NASA Ames in mid-December 2004 [8]. Though the heat flux was only 800 kW/m², the very good behavior of the material during the test confirmed the positive aforementioned statement. Furthermore, in-depth thermocouple data of high quality were acquired. They will allow a cross check validation and consolidation of the thermal model of AQ60, which is currently on-going.

5.3 General status on TPS structure adherence

In parallel, the qualification of the TP/structure interfaces has been reviewed, and the final statement was that a good behavior had been demonstrated up to the specified allowable temperatures.
For higher values, no problem was expected since these allowable temperatures were not too much exceeded, but no experimental results were available to comfort this statement.

6. TEMPERATURE EVALUATIONS

Based on the aforementioned updated heat fluxes, the thermal response of the TPS must be determined on each area of the probe. For the back-cover, complementary analyses concluded around mid-November that heat flux would be lower than initially expected and it was therefore proved that this part would encounter allowable temperatures (<250°C). For the Nose cap area of the Frontshield, previous analyses had already shown that this zone would not bring any problem. Hence attention was mainly paid to the decelerator zone of the Frontshield (so-called mid-cone or flank, and end-cone or shoulder). Fig. 11 below gives an example of temperature evolution on this zone, slightly exceeding the allowable value of 180°C.

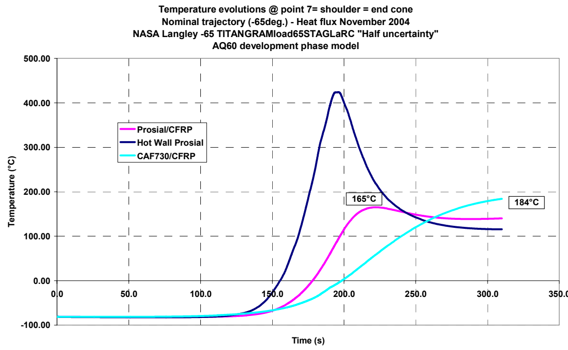

Fig. 11 : Example of temperature evolution of Frontshield (shoulder area)

These analyses were carried out using different sets of hypotheses, according to considered uncertainties for both aerothermal environment and material properties. Fig. 12 and Fig. 13 show two synthesis matrixes that summarize the main results.

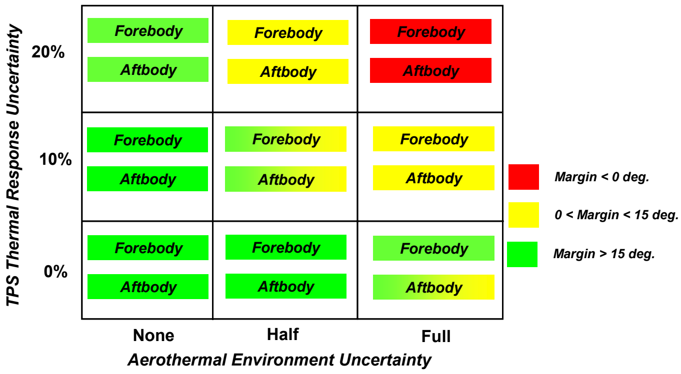

Fig. 12 : Temperature margins accounting for TPS and ATD uncertainties

TPS Thermal Response Uncertainty	None	Half	Full
20%	A20 - Margin Forebody >19°C Aftbody >15°C	B20 – Margin Forebody >5°C Aftbody >7°C	C20 – Margin Forebody <0°C Aftbody <0°C
10%	A10 - Margin Comfortable Based on A20	B10 - Margin Forebody: 26°C Aftbody >16°C	C10 - Margin Forebody: 9°C Aftbody >1°C
0%	A0 - Margin Forebody >42°C Aftbody >34°C	B0 - Margin Comfortable Based on B10	C0 – Margin Forebody >20°C Aftbody >10°C

Aerothermal Environment Uncertainty

Fig. 13 : Temperature margins accounting for TPS and ATD uncertainties.

These analyses were taken into account in the risk analysis carried out at the same time, and for which

the TPS performance was one among the key parameters.
Most cases led to positive margins (Back-Cover, Nose cap area of the Frontshield, Decelerator part of the Frontshield with nominal hypotheses without uncertainties)
However, as the calculated temperatures still exceeded the specifications in some cases, it was not possible to issue a fully positive conclusion at TPS level. The influence of these too high temperatures needed thus to be assessed at system level for linked susbsystems (thermal control during entry, structure behaviour, and particularly consideration of actual low temperatures at the time when mechanical efforts such as parachute opening occur).

7. CONCLUSION OF FLIGHT PREPARATION PHASE

Following the reassessment of TPS performance, the review of development phase qualification, the review of TPS/structure adherence, the demonstration of the opacity of AQ60 to UV radiation, the confidence in the material was sufficient enough in spite of some lack of relevant experimental result.
Subsequently, all the “red flags” at TPS level turned to green lights, and the TPS was declared READY TO OPERATE FOR ENTRY MISSION AT TITAN, before operating successfully on January 14th 2005.

8. LESSONS LEARNED

The mission was successfully concluded on January 14th 2005 and the AQ60 was thus proved to be an appropriate material for planetary entry. However, the lack of temperature measurements in the heatshield will leave many questions open regarding the actual heat flux level encountered by the probe during its entry to Titan and the real margin for the TPS. Therefore, the lessons learned about TPS are not coming from the flight itself but rather from the preceding phases.

8.1 Some considerations about thermal analysis work performed in 2004

A first topic to be addressed is about the philosophy behind thermal analyses. During the development phase, the aim was to design the TPS and optimize the mass. On the other hand, during the mission preparation, the objective was to evaluate the TPS performance, based on the actual manufacturing features of the probe. This analysis could be performed without difficulty in 2004 because the models could be recovered and run easily, with the support of people who prepared them ten years before. However, some preparation of such an exercise just after the manufacturing would have been appropriate for two main reasons:

- As the inspection documentation was not initially devoted to such a study, its exploitation would have been easier at that time.
- This is mainly due to the fact that the background knowledge of some key people is generally also valuable and very useful.

Furthermore, it must be pointed out that some instrumentation of the TPS would have made this analysis mandatory, in order to enable the establishment of test predictions.

8.2 Some considerations following fruitful cooperation with NASA in 2004

Most of tasks performed in 2004 were initiated following recommendations formulated by NASA during the Delta Flight Acceptance Review (feb04). Though it induced high pressure because of the short time before the final phases of the mission, it also generated valuable discussions, showing differences in the development approach and allowing the elaboration of some interesting remarks:

- TP material modeling and qualification: the approach used by EADS-ST for Huygens was rather a direct interpretation of tests results while a more theoretical approach is generally applied by NASA, relying on a more extensive test plan.
- The management of margins would require additional debate for eventual search of more complete harmonization.
- Design based on tiles is considered by NASA as a tricky task with some eventual risk.
- The influence of pressure on the thermophysical characteristics of an ablative TP material is a new element for both NASA & EADS-ST.

Of course, one other key element was the performance of the UV radiation tests that demonstrated that the transparency in the UV range was no longer a concern and the complementary arc jet test, the detailed exploitation of which will bring fruitful results and discussions.

8.3 Specific considerations for aft body

As for many similar studies, the main attention was paid to the front face of heat shield that intuitively seemed more difficult because of a higher heat flux. But the influence of the heating of the aft body was quite a critical point during the last week of TPS performance reassessment.
This was due to a lower robustness in this area to heat flux uncertainties or evolutions, which can easily be explained by the following considerations:

- The uncertainties are higher on aft body heat flux
- The thermal response shows higher sensitivity compared to the fore body, because the effective

part of the entering heat flux is more important due to a much lower radiative reemission σTw^4.

So, even though this area does not look critical at a first glance, especially in term of qualification and/or material behaviour, it is compulsory to have sufficient knowledge and precise characterisation in the appropriate range to apply satisfactory optimisation and safety margin policy.
This is especially interesting because the thermal protection of the aft body represents in most cases important surface areas, which means by the way a significant mass far to be negligible, all the more it leads to move the vehicle CoG backward.

8.4 Concluding Recommendations

The main recommendations issued from the previous sections are summarised in Table 3 below.

Table 3: summary of recommendations and lessons learned about TPS

Design features
- Need to have heat shield instrumentation for next missions - Need to pay more attention to rear TPS
Margin policy
- Interest to have further discussions for harmonization between Europe and the US
Analysis features
- Need to evaluate TPS thermal response with actual manufactured values - Keep in mind that all the background knowledge of key people remains an invaluable support to the best documentation - Need to account for the long time from development to final mission, and eventual consequences (e.g. software evolution)
Material
- AQ60 applicable for eventual future planetary missions

9. ACKNOWLEDGEMENTS

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11. ABBREVIATIONS

ACWG	Aeroheating Convergence Working Group
ATD	Aerothermodynamics
CFRP	Carbon Fibers Reinforced Plastic
CoG	Centre of Gravity
FAR	Flight Acceptance Review
TPS	Thermal Protection System